CHAPTER I

FULL CIRCLE

In the year 1604, Galileo Galilei formulated a law of falling bodies in a letter to his friend, Paolo Sarpi. "I have arrived at a proposition," he wrote, "which is most natural and evident, and assuming it, I can demonstrate the rest; namely, that spaces traversed in natural motion are in the squared proportion of the times, and consequently the spaces traversed in equal times are as the odd numbers beginning with unity. And the principle is this, that the naturally moving body increases its velocity in the proportion that it is distant from the origin of motion." This is a curious statement. For the first part is right, but one cannot explain how Galileo knew it, since it does not in fact follow from the principle, which is wrong. Under uniform acceleration, velocity varies directly as time, not distance, and any schoolboy learns the correct law by rote as either or both of two equations,

\[ s = \frac{1}{2} gt^2 \quad \text{and} \quad s = \frac{1}{2} vt. \]

Even when he finally did get it right, Galileo could not so express it. Algebra had yet to be adapted to description of continuously developing quantities. He disposed only of the resources of ordinary language and of the geometry of Euclid and Archimedes. In 1632, after years of reflection and not a little frustration, he explained the law in Dialogue on the Two Chief Systems of the World, the great Copernican argument over which the Roman Catholic Church humiliated him; and there he repeated, "that the distances passed by the body departing from its rest are
to each other in double proportion of the times in which those distances are measured."

To that, Sagredo, the receptive interlocutor, now responds, "This is truly admirable; and do you say there is a mathematical demonstration for it?" And Galileo gratifies the request he has invited by expressing the relation between velocity, distance, and time as a triangle. Falling from rest at A, the body picks up speed through "infinite degrees of velocity." The time of fall is laid off on the vertical AC. Perpendiculars (DH, EI, etc.) represent the velocity after time AD, DE, etc., and the whole triangle is "the mass and sum of the whole velocity, with which in the time AC it passed such a certain space." Or, to put it otherwise, the area of the triangle \(\frac{1}{2}vt\) measures the distance traversed. And to find the distances travelled by a body moving at uniform velocity (BC), the triangle may be doubled into a rectangle (ACBM).

But though perfectly correct, this must still seem painful and clumsy to the modern reader. Velocity appears as one variable and time as the other, whereas it has become customary to think of velocity rather as a ratio of distance to time. Moreover, it measures the linear distance \(s\) by an area. Nor does the geometry yet derive the law in the form which relates distance to acceleration \((s = \frac{1}{2}gt^2)\). In 1638, Galileo published his final and scientifically his finest work, *Discourses on Two New Sciences*. There at last he achieved an explicit statement of both common forms of the law. The discussions of the "Third Day" work towards a renewed demonstration of the velocity-time relationship, in more elegant geometrical form than in the *Dialogue*, and in less elegant language. Next, Galileo proved what until now he had only asserted: the distances are as the squares of the times. This was far more difficult. He had to formulate graphically what he called "uniformly
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diform motion,” that is to say, a dynamical proposition involving acceleration in the essentially static forms of plane geometry.

He represented the “flow of time” by simple extension, the line AB, on which AD and AE measure any two intervals. To the right, the line HI stands for the path of descent at uniform acceleration, so that HL is the distance traversed in time AD, HM in AE, etc. These things being so, then “I say that the space MH to the space HL is in the duplicate ratio that time AE has to time AD.” For, construct AC at any angle to AB. Then DO, EP, etc. will again represent maximum velocity at corresponding time. It followed from the previous (mean-speed) theorem that the spaces are equal which are traversed by one body at uniform acceleration from rest, and a second moving at a constant velocity which is one-half the maximum attained by the first. Thus, the distances of fall HL and HM would be equal to those traversed in times AD and AE at constant velocities one-half of DO and EP respectivity. But it had already been shown that the distances passed by two bodies in uniform motion are to each other as the product of the ratio of the velocities into the ratio of the times. Now, since EP is to OD as AE is to AD, then the ratio of velocities is in this case the same as the ratio of the times. “Therefore, the ratio of the spaces traversed is as the square of the ratio of the times. Q. E. D.”

At this point, Salviati, who speaks for Galileo, stops the dialogue as if a light had dawned: “Please suspend your lecture for a moment while I speculate on a certain idea that has just now occurred to me.” And he puts the two forms of the law together. AI represents time again, AF is at any angle, and C is the mid-point of AI. Then
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(to condense the argument a bit), if the body falls freely to C, BC will be the maximum velocity, and the distance will be measured by the rectangle of uniform velocity erected on the base EC equal to \( \frac{1}{2} \) CB.

Moreover, if the body continued its descent at constant velocity BC, then in the interval CI it would cover twice the distance that it had described in time AC, starting from rest. But since the body is under uniform acceleration, its velocity during the time CI will increase by an amount FG equal to the parallel of the triangle BFG, which is equal to ABC. Then, adding to velocity GI (equal to BC) half of FG, which is the maximum velocity attained through acceleration, one gets the uniform velocity with which the same space would have been described in the time CI. And perhaps the drift is apparent without further paraphrasing. The rectangular areas which represent the space described increase in successive time intervals, "as the odd numbers beginning with unity, 1, 3, 5; ... and in general, the spaces traversed are in the duplicate ratio of the times, i.e., as the squares of these times."

These figures represent the earliest integrations applied to developing physical quantities and may be taken, therefore, to symbolize the germ from which has grown a mathematical science, not alone of proportions, but of nature. For there was nothing novel about expressing uniform motion in the abstract as a ratio of change in geometrical quantities. Galileo's first triangle of motion was a mathematical commonplace, generally called the Merton Rule after the school of kinematic philosophy which flourished in that ancient Oxford College during the fourteenth century. Moreover, the mean speed theorem reduces to the law of acceleration, and needed rather to
be stated helpfully than to be discovered. Everything, indeed, or nearly everything, that Galileo put together may be found in the writings of one or another of the late scholastics, in the aphorisms of Leonardo da Vinci, or in the works of some predecessor among the Renaissance mathematicians. But only Galileo, and he only after many a false start, developed the judgment and intuition and feel for the physical to select the elements of a physics from this *olla podrida* of mathematical techniques and philosophical assertions. His was the transforming touch of the mathematical physicist, the first of his kind, who would really change a situation instead of simply entering a discussion. That touch reveals itself thrice over in these passages. First, he derived the rule of uniform acceleration in a form applicable to freely-falling bodies. Then he included it in a general statement containing both the velocity-time and the acceleration-time-squared measures of path. Finally he applied it to the real case in nature and therein lay his genius.

For only Galileo would have given the discussion the turn it takes immediately after the last of these, his mathematical demonstrations. Simplicio, who upholds the Aristotelian case, bows before the force of geometry, “so that I am convinced that matters are as described, once having accepted the definition of uniformly accelerated motion. But as to whether this acceleration is that which one meets in nature in the case of falling bodies, I am still doubtful; and it seems to me, not only for my own sake, but also for all those who think as I do, that this would be the proper moment to introduce one of those experiments—and there are many of them, I understand—which illustrate in several ways the conclusions reached.” And Galileo reports on the famous experiments on inclined planes which he had imagined, and some of which he may quite probably have actually performed.
THESE WERE PORTENTOUS TRIANGLES. To the historian thinking broadly about the recent destiny and future prospects of western civilization, it may well appear that our own culture, in which whatever our temperament we are bound to live, is set off from those of Asia, Africa, and the world of antiquity by two fundamental factors. From one of these it emerged: its religious chrysalis was Christianity, investing history with the promise of fulfillment of a sort. The other it produced: the most dynamic, distinctive, and influential creation of the western mind is a progressive science of nature. Only there in the technical realm, indeed, does the favorite western idea of progress hold any demonstrable meaning. No one understands political power better than Machiavelli did. Picasso cannot conclusively be held a better or worse artist than Leonardo was. But every college freshman knows more physics than Galileo knew, whose claim is higher than any other’s to the honor of having founded modern science, and more too than Newton did, whose mind was the most powerful ever to have addressed itself to nature.

In its early days, science was distinct from technology, springing rather from thought and philosophy than from craftsmanship. Nowadays, however, and indeed for the last century and more, science has merged ever more intimately with technology, so arming it with power, so enhancing its capacities, that no words, nor any fears or dreams, may exaggerate what depends upon the employment. Nor is the future of our own world of the West alone in play through this, its great invention. Perhaps the historian may be pardoned a single prophecy, if it comes at the beginning of a book before his tale has made him pompous. Anxious though our moments are, today is not the final test of wisdom among statesmen or virtue among peoples. The hard trial will begin when the instruments of power created by the West come fully into the hands of men not
of the West, formed in cultures and religions which leave them quite devoid of the western sense of some ultimate responsibility to man in history. That secular legacy of Christianity still restrains our world in some slight measure, however self-righteous it may have become on the one side, and however vestigial on the other. Men of other traditions can and do appropriate our science and technology, but not our history or values. And what will the day hold when China wields the bomb? And Egypt? Will Aurora light a rosy-fingered dawn out of the East? Or will Nemesis?

Albert Einstein once remarked that there is no difficulty in understanding why China or India did not create science. The problem is rather why Europe did, for science is a most arduous and unlikely undertaking. The answer lies in Greece. Ultimately science derives from the legacy of Greek philosophy. The Egyptians, it is true, developed surveying techniques and conducted certain surgical operations with notable finesse. The Babylonians disposed of numerical devices of great ingenuity for predicting the patterns of the planets. But no Oriental civilization graduated beyond technique or thaumaturgy to curiosity about things in general. Of all the triumphs of the speculative genius of Greece, the most unexpected, the most truly novel, was precisely its rational conception of the cosmos as an orderly whole working by laws discoverable in thought. The Greek transition from myth to knowledge was the origin of science as of philosophy. Indeed, knowledge of nature formed part of philosophy until they parted company in the scientific revolution of the seventeenth century.

In our own world, science continues to be what it was in Greece, conceptual thought mediating between consciousness and nature. But it is also something more. It has become determinate instead of simply speculative.
For the scientific revolution reversed the direction in which information flows, and added body to the structure of communication. Greek science was subjective, rational, and purely intellectual. It started inside the mind whence concepts like purpose, soul, life, and organism were projected outward to explain phenomena in the familiar terms of self-knowledge. In those terms the success of an explanation depended only on its universality and capacity to satisfy the reason. Greek science scarcely knew experiment and never thought to move beyond curiosity to power. Modern science, on the other hand, is impersonal and objective. It takes its starting points outside the mind in nature and winnows observations of events which it gathers under concepts, to be expressed mathematically if possible and tested experimentally by their success in predicting new events and suggesting new concepts. Modern science has not abandoned rationality, but it is first of all metrical and experiential. Related to this is its association with technology as a continuation of that generalized thrust toward mastery of the world which began in the West with the Renaissance. Modern science, finally, seeks both to comprehend and control nature—though according to the positivist school of philosophers, whose persuasion dominates at the moment, comprehension is an illusory goal. For them prediction and control are everything.

A true revolution brings fundamental change through rebellion against constituted authority, but it is clear from the history of revolutions that to repudiate a debt is not to escape it. So it was that the creation of modern science in the Renaissance was at once a rebirth of Greek science and a bursting of its confines. To separate the new from the old in the Renaissance is always difficult, for humanists steeped in classical learning found antique words for new ideas. It is, however, no falsification of a complex situa-
tion—it is rather a first approximation toward resolving it—to say that science stirred into new life under the inspiration of Plato working against the cramping of learning within a fossilized Aristotelianism.

By Galileo's time, the science and authority of Aristotle had led the western mind a long way to a dead end. Aristotle's was the most capacious of philosophies. In principle it explained everything, dealing rather in reasons than structures, and preferring categories over abstractions. For example, Galileo could describe mathematically how a stone would fall under ideal conditions. He could not say why it fell. Aristotle's physics, on the contrary, could not measure its motion. But this was not to be expected in a real world of friction and complexity where ideal conditions never occur. Aristotle could do more important things. He could explain why a stone fell, why sparks flew upward, and why the stars ran round in their courses.

Beneath its physical manifestation as translation, Aristotelian motion is metaphysical, an instance of change, an evidence of imperfection. Change is the act of things realizing their potentialities in a world striving ever to fulfill its creator's will toward order, which is toward the good, so far as its corruption permits. In an orderly cosmos there is by definition a place for everything. Heavy things belong at the bottom. To say that the stone falls because it is of the class of things which are heavy constitutes, therefore, a full explanation. So, too, fire rises because it is light. The locus of that element is in the ethereal region, with air below it, water below that, and crude earth massed round the center. But what of an arrow? Here a distinction of motions must be introduced. Its motion is not natural but forced, not orderly but disorderly and violent. It must have a cause. Logic requires effects not to outlast their causes. Therefore, every motion against nature presupposes a moving agent, and demands explanation.
What, then, moves the arrow after it has parted from the bow-string? In a philosophy which is nothing if not universal, to have no answer would be to have no science, and after some hesitation, Aristotle meets the dynamical difficulty with the air. It is the surrounding medium closing in behind the projectile which urges it along its way. There can, therefore, be no motion in a void. There cannot even be natural motion, for in this case the medium serves to retard the body. In a vacuum a stone would fall instantaneously. Since that is absurd, nature knows no void, and the world must be a plenum, finite and by later standards rather small. But the inadmissibility of the void goes deeper than abhorrence of the vacuum. It goes all the way to the foundations. There is no such thing as place in a void, and the goal of this philosophy was to define the right and necessary place for every species of being according to the purpose that it served. Nor can there be existence in the nothing. In a void no stone could tell where to go, no flame find the way to leap. The very notion of direction or order would become meaningless. To admit the void is to accept the reign of chaos, wherein whirl is king, in lieu of our own world full of meaning.

So it is throughout Aristotle's physics. It was a serious physics, a consistent and highly elaborated ideation of natural phenomena. It started from experience apprehended by common sense, and moved through definition, classification, and deduction to logical demonstration. Its instrument was the syllogism rather than the experiment or the equation. Its goal was to achieve a rational explanation of the world by showing how the myriad subordinate means are adapted to the larger end of order. Its operations were suited to these interests. Direct and minute observation, classification of forms by species, analysis of how the part serves the whole—these are useful acts up to a point in natural history, as the description of life and
its environment was called until the nineteenth century. Not till then was biology ready to transcend the Aristotelian sense of purpose in nature and follow physics into objectivity. Aristotelian physics, too, had immense humane advantages denied to that which has supervened since Galileo. It easily fell in with a sense of Providence in nature. As the physical system sheltering the world view of Islam, Judaism, and Christianity, it became the scientific orthodoxy of all three religions which shaped the West in its emergence from the dark centuries after Rome. For Aristotelian physics made sense of the world and strengthened the hands of men of God and all those striving to redeem civilization, culture, and truth from barbarism.

There was only one trouble. It was wrong. For however congenial Aristotelian physics was to the self-knowledge of the minds that elaborated it, nature is not like that, not an enlargement of common sense arrangements, not an extension of consciousness and human purposes. She is more elusive, more coquettish perhaps and infinitely more subtle, hiding her ways from the merely dogged or the worthy, and only occasionally yielding to the truly curious those glimpses of great order and altogether inhuman beauty which are the reward of him who strikes the right note, and all the reward he seeks—that and fame. But who, asked James Clerk Maxwell two millennia later, “who will lead me into that still more hidden and dimmer region where Thought weds Fact, where the mental operation of the mathematician and the physical action of the molecules are seen in their true relation?” For the order is mathematical and the notes harmonious, Platonic rather than Aristotelian.

Not that Plato and Aristotle differed on all fundamentals. They were teacher and pupil. To both, nature appeared as the creation of artful mind, and order as the expression of rationality. Both took a humanistic rather
than a naturalistic view of science. By explanation, both meant identification of what lofty purpose would reveal divine intelligence. But Aristotle addressed himself to physical and biological contrivance, and Plato to ideal being. Unlike Aristotle, Plato did not make a science. He inspired one—in Archimedes perhaps, and much later in Galileo certainly. His influence was less and more, the spell he cast over posterity at once sterilizing and stimulating: sterilizing in that he takes truth out of the world of things, stimulating in that he identifies ideal simplicity with mathematical reality. He speaks poetically to an aesthetic vision of nature, but never to common sense, which in puzzling he offends. What is truth, then, and what the good? They are the eternal and the perfect, being not becoming. The real is the ideal, and change the mirror of corruption. For Aristotle had simply transposed Plato’s metaphysics into physical terms so as to make a distinction between cosmology and physics, the one concerned with the heavenly regions beyond the moon, the other with our sublunary sphere where different laws obtain, where everything is mortal and contingent. Thus was the uniform cosmos of the earliest Greek philosophers dichotomized, and the chance missed of laying down a single science of heaven and earth. In science, Aristotelian kinematics was the most influential consequence of this distrust of change as prima facie evidence of imperfection. Only one motion is perfect in Plato, in Aristotle, and after them down to Kepler and the seventeenth century, namely circular motion, that by which the heavens go, for only in circles can motion occur as changelessness. “God is always geometrizing,” Plato is supposed to have said. This, along with admiration for circles, Plato drew from the school of Pythagoras, in whose semi-legendary figure science retreats into a prehistoric mélange of myth, mysticism, and mathematics. In the search conducted by
the pre-Socratic philosophers for the principle of unity in nature, the Pythagoreans hit upon the assertion that nature is made of number and that numbers have shape. In their eyes, the world is actually made of lines, triangles, squares, cubes, and circles, even as the nineteenth-century physicist might think it made of ninety-two varieties of material atoms. Numbers contain the form of things, at once real and ideal. In numbers lie the clean, eternal structures beneath the welter of appearance. Discovery of the irrationality of the square root of two, and of incommensurable quantities in general, is always described as having shocked this faith. But the shock helped, for it led to appreciation of geometric ratios like the Merton rule of motion, which would give Galileo his mathematical description of falling bodies. Indeed, the Pythagoreans may themselves have been the ones to make the first statement of physics as we know it. They studied stringed instruments and found the relationship between the length of a vibrating string and the pitch it emits, and thus they expressed the experience of harmony as a geometrical quantity. Nevertheless, like the influence of Plato after them, and in fact through Plato, their legacy moved down into the underworld of science, as well as out into its sane and wholesome reaches. As the misbegotten twin of a mathematical physics, they spawned the secret mania of numerology. Nostradamus was their heir as well as Galileo. Rosicrucianism is their progeny as well as relativity.

The two greatest of the Greek philosophical traditions laid ancient science under one final limitation. It was impossible in principle for either Plato or Aristotle to have made a mathematical physics because they agreed that mathematics and physics do not fit, and differed only over which was at fault. For Plato, mathematical relationships are eternal, ideal, and therefore real and true. But there is no such certainty, indeed no certainty at all, in the
world of things, and physics is at best a "likely story." For Aristotle, on the contrary, it is physics which deals with the real. Mathematics is true, to be sure, but only in the abstract. The world itself is made of qualities and forms and fine distinctions which may not be expressed in the precise, quantitative, absolutely unreal terms of mathematics. Ontologically speaking, ancient science fell between these stools. Archimedes might have retrieved it. His was a scientific intellect of the very highest order. In discernment and power, he was the peer of an Einstein. Everyone will recognize that the law of the lever, and more generally the principles of simple machines, represent just that marriage of geometry to physical objects which both Plato and Aristotle held to be impossible. Archimedes arrived at the concept of statical moment by abstracting from physical weight and combining its quantity with geometrical length in Euclidean ratios. Reciprocally, the Archimedean determination of the center of gravity of geometric figures introduced physical intuition into a mathematical problem. But Archimedes came late, the lamp was burning low, and his best pupil was Galileo, seventeen hundred years later, who set statics into motion to found our science of mechanics.

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\[ \text{So far as physics was concerned, the scientific revolution occurred on two levels, cosmology and dynamics. It would be complete only when Newton's law of gravity united knowledge of heaven and earth, separate since Aristotle, into a single theoretical science of matter in motion. On both levels, the revolutionary inspiration came from Platonic criticism playing a ray of mathematical realism upon the vast mass of verbal distinctions into which Aristotelian natural philosophy had proliferated in the late Middle Ages, and from which it endlessly drew theological} \]
tidbits out of nature. Ultimately, dynamics proved the deeper level of scientific thought. But cosmology was the more dramatic.

The Renaissance inherited a complex situation in cosmology. The Aristotelian model of the universe was the well-known Chinese nest of crystalline spheres concentric about a logy, corrupt, and stationary earth. Each carried like luminous studs the moon, the sun, a planet, or the pattern of the fixed stars. Spin was communicated to the whole complex by an outermost shell. Beyond lay bliss. Borne in on every hand, by théology, poetry, literature, and philosophy, this gave the educated man his gross picture of the cosmos. It made sense of the diurnal motion of the heavens, but was no use to astronomers who had to follow and predict the visible motions of the planets along the zodiac. They advance at varying velocities, slowing at times to a pause and retreating a little before going forward once again. These inequalities are the projection onto each planet of the orbital motion of the earth. Appearances were further complicated by slight variations in latitude and by the uncertainty of all data. It is a myth that the ancients were accurate observers. Least important as a source of error was the actual ellipticity of orbits, for the amount by which they do depart from the circular was within the margin of error that this astronomy had to tolerate. The gravest irregularities, the retrograde motions of the planets, might have been saved by a heliocentric model of the solar system. The Pythagoreans are said to have believed in a central sun, and Aristarchos of Samos certainly proposed such a theory in the third century before Christ. But it was stillborn, and instead, astronomers saved the immobile earth for common sense by using in practice the purely geometric astronomy of Claudius Ptolemy.

Ptolemy compounded the apparent movements of each
heavenly body from combinations of circular figures. He employed three devices, epicycle, eccentric, and equant. The epicycle places the planet on a small circle, the center of which describes a large circle called the deferent about the ultimate center of motion. The eccentric makes that center of motion in a particular case some point apart from the center of the earth. The equant is a point other than the center so taken that there is a uniform rate of increase in the angle formed by the diameter through the equant and a line joining it to a point on the circumference. Combinations of epicycles on epicycles, epicycles on eccentrics or equants, and whatnot, to the number of seventy-odd distinct constructions, gave an account of the anomalies. The geometrical virtuosity was admirable. It saved the phenomena, and the proto-positivist physics of the likely story asked nothing more. Moreover, it worked well enough to sustain the calculation of the calendar from Roman antiquity to the sixteenth century, when at last the accumulation of error exceeded the tolerable. Indeed, navigation is still practised as if the earth were at the center of the great display of celestial bearings.

Any revolution has deep roots in culture but begins with some definite act, often meant to purify corrupt practices and restore what some conservative radical
imagines as a pristine state of things. In 1543 Nicolas Kopernigk, Copernicus as he latinized himself, published *De revolutionibus orbium coelestium libri sex*. It is an extremely difficult book. Nor have many or perhaps any modern writers, and certainly not the present one, combined in their own understandings the sympathy, the scholasticism, the latinity, the astronomy, the trigonometry, and the gothicism which would permit them to penetrate the true spirit of Copernicus's life-work. But it does seem tolerably clear that astronomically he was just such a puritanical reactionary, at whose hand the old forms lost not only accretions but their rationale, and began giving way to new.

No scientist, in any case, has ever addressed himself to problems of greater magnitude relative to the state of knowledge. His theory rearranged the solar system and set the immobile earth to spinning daily on its axis while revolving annually about the sun, which replaced it at the center. That is a great and gross difference, and no denigrations must be allowed to obscure it, whether they refer to the conservatism of his mathematics, the obsessive circularity of his kinematics, or the monkish timidity of his life. Stock objections blocked assent for about a century, and to rehearse them will suggest how strongly his ideas had to swim upstream against the tide of common sense. Nor, in the absence of the principle of inertia and the composition of motions, is it any wonder that he tended to falter and keep his notions to himself. For on a moving earth we ought to feel ourselves rushing through the air. A stone dropped from a tower should land to the west of it. Cannonballs fired west should travel farther under the same charge than those fired east. The earth should whirl itself to pieces. We should all fly off like pebbles from a sling. "Those experiences," wrote Galileo just ninety years later, "which overtly contradict the annual
motion of the Earth, have so much more of the appearance of convincingness, that I cannot find any bounds for my admiration how reason was able in Aristarchos and Copernicus to commit such a rape upon their senses as, in despite thereof, to make herself mistress of their belief." Even deeper, though less seriously intuitive than our feeling of immobility, was the prejudice against the unworthiness of the earth to be moving in circles through the heavens, that being a motion suited only to aethereal and immaterial bodies.

A Polish scholar, Copernicus was educated in Cracow, Bologna, and Padua. His father had died when he was a boy in Thorn, and he became the charge and protégé of an uncle, Lucas Watzelrode, an ecclesiastical statesman and a considerable figure in the Baltic world where the jurisdictions of Poland, the Church, and the military order of the Teutonic Knights mingled in late medieval confusion. Watzelrode became sovereign bishop of Ermland, an ecclesiastical principality with a narrow outlet to the Baltic at the cathedral town of Frauenburg. There Watzelrode arranged a canonry or prebend in the chapter for his nephew. For years Copernicus held his prebend as an absentee, loath like many a Pole and German before and since to return from Italy, where he went in 1496 immediately after his election. At Bologna and at Padua Copernicus was educated as a humanist in classics, medicine, geometry, and astronomy, and his intellectual world, perhaps even his spiritual world, was that of Greek and Latin antiquity. Later, he did into Latin a book of epistles on moral, pastoral, and mildly amorous subjects by one Theophylactus, an obscure Byzantine writer of the seventh century. But only in astronomy did Copernicus display the taste to select from antique learning that which would truly enter into the Renaissance movement to renew the world. And if like a good humanist he invoked in Aristarchos the license of antiquity, his originality is no more
ambiguous than that of the whole culture of the Renaissance in its Janus posture. For Copernicus made heliocentricity part of science and not just speculation. With him it enters into the structure of the progressive knowledge of nature. His work added a determinate element. The whole history of science is his vindication, and criticism, therefore, must try to say what that element was.

There is evidence that he experienced the simplicity and elegance of the Aristarchan idea as early as 1505 or 1506. The preface to his *Revolutions* says that he had kept the idea by him, not just for nine years as the Pythagoreans had enjoined, but for four times nine. It may have come to him like some conversion, just as he was about to depart for home. He had then spent his ten years in the sun, and in the open intellectual climate of Italy. If the great idea did occur in such fashion, it makes an affecting picture. He never left Poland again. There he
spent the rest of his life, on that Baltic shore, living at his uncle’s residence in crabbed little Heilsburg until Watzenrode’s death in 1512, thereafter inhabiting a tower room in the crenellated wall of crabbed little Frauenburg. He would take an occasional hand in the Graustarkian governance and diplomacy of Ermland. He would peer through the mists and pore over Ptolemy and the tables of astronomy in a mood of gathering distaste. For Copernicus studied the figures, not the stars. And he worked at his system, which he intended to be more than an alternative set of geometrical hypotheses. He meant it as a real system of astronomy, to supplant the Ptolemaic devices used by astronomers, navigators, and calendars and to be, moreover, a true representation of the physical relations of sun, earth, moon, and planets.

Inevitably, the facts and figures were recalcitrant. Many were quite wrong. The execution of the work could not bear out the grand simplicity of its leading idea. That he stuck to that idea in the teeth of all the difficulties, daunted but not defeated by discrepancies, might be taken, perhaps, as a testimonial to the rationalizing role of theory in science, and to the virtue of a faith in some ultimate reason in things. It is no wonder that on completion of the work in 1532 or thereabouts, he hesitated to publish, and alluded now and again to legendary Pythagorean injunctions to secrecy. But he had not refrained from all communication. Quite early, probably in 1512, he circulated a sketch of his theory in manuscript. The Commentariolus it is called. News of his ideas spread in the gossipy world of Renaissance scholarship, widely enough for Luther to pass his famous remark about some fool who “went against Holy Writ.” Then in 1539 there arrived in Frauenburg one Georg Joachim Rheticus (as he called himself after his birthplace, though his real name was von Lauchen), a young professor of mathematics from Wittenberg, pow-
erfully attracted to the rumors of heliocentricity, and all eagerness to learn what substance they might hold. Copernicus admitted him to scientific intimacy. Together they reviewed the data. Rheticus published the first authorized account, the *Narratio Prima*, at Dantzig in 1540.

Its success, or perhaps the urgings of Rheticus and other friends, persuaded Copernicus to commit his full treatise to the press. It is divided into six books. Book I contains a general description of the system of the world: the sun and not the earth is the center; what appears as the daily rotation of all the heavens is the effect of the earth's spinning on its axis; the annual motion of the sun is the appearance of the actual revolution of the earth annually; the advances and retrogressions of the planets are projections of the same cause combined with their own motions; the distance from the sun to the earth or planets is very small compared to the remoteness of the fixed stars. Book II contains a star catalogue compiled from ancient and more recent astronomy, from which Copernicus computed the elements of the year. The remaining four books contain detailed mathematical theories, which is to say geometric devices and trigonometrical methods, for predicting the motions of the planets referred to the earth and to the sun, together with the real motions of the earth and moon. Printing was completed in Nuremberg in 1543, under the supervision of Andreas Osiander, a friend of Rheticus and a Lutheran theologian. He took the precaution, or the liberty, of adding a disarming preface to the effect that the author claimed for his system only mathematical convenience, not truth. This was incorrect. Copernicus was a mathematical realist in the Pythagorean tradition according to which figure and number contain the structure of things. But he never read the preface which said that his book was not true, nor the book itself, for he had been stricken by cerebral haemorrhage and lay
on his deathbed when the first printed copy reached Frauenburg.

The Copernican Revolutions is a great work of science. Like all great works, it has had to survive a certain tradition of belittling scholarship, which in this case seems to imply that there was no real reason to prefer the heliocentric to the geocentric model, the two being geometrically interchangeable. Nor is the merit of Copernicus very evident when it is made to rest on simplicity in computation and economy in celestial motions. What with his reliance upon Ptolemaic data, his humanist’s deference for antique learning, and his own belief in circularity as the heavenly pattern, Copernicus saved nothing significant in motions out of the long years during which he struggled through thickets of computation. He had the misfortune, indeed, to complicate his problem unnecessarily by adding to the rotation and revolution of the earth a third motion, a top-like wobble, whereby the equinoxes precess (which did require some account) and the north pole points to Polaris on both sides of the orbit (which did not). Nor will the superiority of Copernicus appear in a game of counting epicycles between Ptolemy’s astronomy and his, the low score winning.

Copernicus, indeed, cannot satisfy such critics, for his criterion of elegance was different. It was not by eliminating epicycles that he thought to simplify and rationalize the procedures of astronomy: rather, it was by discerning the structure in things which befits the foundation of order. That foundation was the circle, the perfect figure. And it is the principle of circularity rather than of economy which conveys the inwardness of his vision of the world. Facts are pesky. Copernicus would subdue them by the epicycle. He would arrange them by the eccentric. And he did have to place the center of the orbit of the earth at a geometric point outside the sun in open space. But what had mortally
insulted him in Ptolemaic astronomy was the equant. This saves the appearance of variable velocity by differentiating between uniform and circular motion. Copernicus thought it a cheat. In order to eliminate the equant, he added eccentrics and epicycles, and thus he lost to circularity motions that he had gained by sending the earth around the sun.

The superiority of the Copernican system, therefore, was conceptual rather than actual. Its vindication lay in the future when the data would be perfected, not in the past whence came its inspiration. Kepler might conceivably have proved that the sun goes around the earth in an ellipse. In a sense it does. But he could not have proved that Mars goes around the earth in an ellipse, because it does not. Moreover, there were important empirical respects in which the Copernican system actually was the simpler. With all the complications in detail, it exhibited one grand regularity which the Ptolemaic did not. The periods of revolution of the planets followed the same order as their distance from the center—the greater the radius, the longer the year. Given the complications of both systems, the effective radius was no simple line, of course, and the comparison might be made somewhat differently. In the Copernican system the angles subtended at the outer planets by the orbit of the earth exactly equalled the Ptolemaic angle subtended at the earth by the respective epicycles. Thus, in the Copernican system the relative contribution of the epicycle to the theory of each planet diminishes with the distance from the sun, while that of the deferent increases. As for the inner planets, it was a suspicious feature of the Ptolemaic construction that their deferents both equal that of the sun. Further, the Copernican order explained much more naturally why the sun and moon never appear to reverse their direction along the zodiac. And finally, it was far more reason-
able—as Copernicus insisted—to think of the earth spinning daily, than to imagine what velocity such a rotation would impose upon the fixed stars.

These solid reasons will seem more persuasive in retrospect than will the Copernican aesthetic. Copernicus had steeped himself in the Pythagorean cult, Christianized in neo-Platonism. The sun itself had been the object of Pythagorean worship. In the tradition of Christian mysticism, illumination became the light of truth permeating the soul. And for Copernicus no arrangement was thinkable but that the sun, the lamp of the world, should occupy its center:

In the middle of all sits the Sun on his throne. In this loveliest of temples, could we place the luminary in any more appropriate place so that he may light the whole simultaneously. Rightly is he called the Lamp, the Mind, the Ruler of the Universe: Hermes Trismegistus entitles him the God Visible. Sophocles' Electra names him the All-seeing. Thus does the Sun sit as upon a royal dais ruling his children the planets which circle about him.

But there is something meretricious about all this by the sixteenth century, or so it seems, and it is fortunate for the reputation of Copernicus that it does not have to rest upon his attainments in literature or philosophy.

Thus far our concern is with geometric conservatism tempered by a touch of sun-worshipping superstition. What, then, was determinate? What was there in the celestial gyroscopics of Copernicus to speak with such authority to the physical intuition of a Kepler or a Galileo? And ultimately it was just that, the physical element in his imagination, all wrong though it was, which seems to mark Copernicus out from the antique, whence he took data and techniques, and to lead forward into science. For his theory associated real physical events with a mathematical formalism. He needed something to make the
earth turn, the earth and the celestial orbs, which he thought to be actual structures. He never looked beyond geometry, and based his kinematics as well as his computations upon circles. "Rotation is natural to a sphere," he boldly wrote, "and by that very act is its shape expressed." Put a globe in space, it will spin. This may not help much in the interpretation of nature, but it is the key to the interpretation of Copernicus. There was, moreover, one very important respect in which Copernican astronomy did enter into the development of physics, even if only critically. It was subversive of Aristotelian order. In a Copernican universe no physics could survive which depended on a central earth as the locus of the heavy. Not that many persons saw the point, or could yet relate celestial motions to terrestrial physics. But for cosmology too, the implications went beyond the choice of geometrical systems. Where does the world begin or end, if the earth is not the center? How deep are the stars set into space, if they are not pinpricks on the dome of the cosmos? Copernicus never said. One objection to his theory was that the stars show no annual parallax to the unaided eye. He met it by moving them out in hypothesis to where a parallax would be unobservable. And though the imagination could scarcely fail to travel on to an infinity of space and worlds (and created beings?), he wisely left that alarming prospect for more adventurous philosophers to discuss, one of whom, Giordano Bruno, burned for his temerity in the first year of the new century. (CONTINUED...)

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